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The Solar Mass Ejection Imager (SMEI): Development and Use in Space Weather Forecasting

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Abstract. The Solar Mass Ejection Imager (SMEI) experiment will measure plasma features traversing the heliosphere, including coronal mass ejections (CMEs), shock waves, and structures such as streamers which corotate with the Sun. SMEI will measure propagation characteristics of these features providing one to three day forecasts of their arrival at Earth. The white light photometers on the HELIOS spacecraft demonstrated that electronic cameras, baffled to remove scattered light, can sense visible sunlight scattered from the free electrons of solar ejecta propagating through interplanetary space. SMEI promises a hundred-fold improvement over HELIOS, making possible quantitative studies of mass ejections. SMEI is highly complementary to other satellite missions, the Global Geospace Program (GGS), and the National Space Weather Program. When coordinated with the imaging and in situ experiments on SOHO, TRACE, WIND, ULYSSES, and SXI SMEI will greatly enhance the GGS program by predicting the rate of energy transfer from transient interplanetary disturbances into the Earth's magnetospheric system being monitored by GGS satellites. The SMEI data will assist researchers in establishing quantitative relationships between solar drivers and terrestrial effects.

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1. Introduction

1.1. Background

SMEI is an imaging instrument designed to view the entire sky, particularly transient heliospheric disturbances ejected from the Sun and affecting the Earth's environment. SMEI will detect, measure, track and forecast the arrival at Earth of solar mass ejections and

solar plasma traveling at several hundred to $> 1000\ km\ s^{-1}$, with embedded magnetic fields, and can cause geomagnetic disturbances on arrival at Earth. CMEs often drive interplanetary shock waves, and these dense fast clouds produce the largest geomagnetic storms. There is currently no reliable way to predict arrival of these disturbances at Earth or to study them in the inner heliosphere. Fig. 1 illustrates a Sun-centered sky map showing how SMEI can distinguish a CME that will impact the Earth from one that will not.

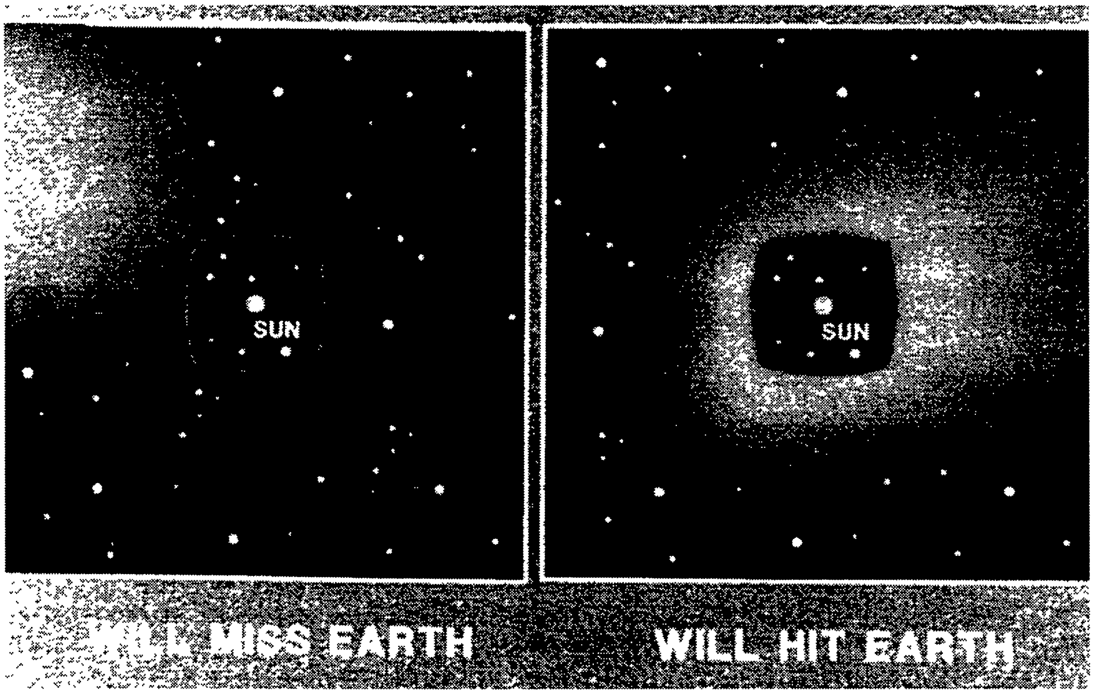

Figure 1. Artist Conception of mass ejections that will hit and miss the Earth. Depiction of two solar mass ejections as they approach the vicinity of the Earth and are imaged by the SMEI experiment. The FOV is 120° square and the inner box, showing the area blocked to avoid scattered sunlight, is about 40° square. Such maps would allow us to predict that the CME on the left would miss the Earth, while the one on the right would impact the Earth.

SMEI records the Thomson-scattered signal, or brightness from free electrons in the interplanetary medium (IPM). In principle it operates like a solar coronagraph, but its design heritage follows directly from the HELIOS zodiacal light photometer experiment. There are several papers describing the SMEI experiment and the requirements it must meet to measure CMEs (cf. Jackson et al. 1987: Jackson 1988; Jackson et al. 1989; Jackson et al. 1991). Development of the SMEI instrument is now underway, with a goal of launching before the next solar maximum. This paper reviews the SMEI concept and its role in space weather forecasting.

1.2. Heritage of Instrument

The basic operating principle of SMEI is derived from broadband, white light coronagraphs which artificially occult the bright solar disk to allow viewing of the inner solar corona. Coronagraphs operate on the principle of imaging coronal structures by detection of photospheric light scattered from the free electrons (Thomson scattering) in the denser, hot structures. CMEs were first analyzed in detail using the Skylab coronagraph, and such coronagraphs are still the best way to view these huge ejections of material near the Sun.

The twin European HELIOS interplanetary probes were launched into solar orbits between 0.3 and 1 AU, in the 1970's. One of the goals of this mission was the measurement of the Zodiacal Light, but when the data were reduced, it was noticed that time-dependent fluctuations were present. Further analysis showed that these fluctuations were due to scattering of sunlight from clouds of interplanetary electrons, i.e., again via the Thomson scattering process (Richter et al. 1982). The clouds have been identified as having distinct solar origins: CMEs; high-density, corotating, dense elongated regions (streamers or stream interfaces); and interplanetary shock waves. HELIOS data have proven to be extremely useful in measuring and understanding the characteristics of such features in the inner heliosphere (e.g., Jackson & Leinert 1985; Jackson 1985; 1986a and b; Webb & Jackson 1990; Jackson, 1991; Hick et al. 1992; Jackson et al. 1993; Jackson et al. 1994a; Webb & Jackson 1992; 1993; Webb et al. 1993; and Jackson et al. 1994b). The HELIOS probes have both ceased operation.

Based on the success of HELIOS, we have designed an advanced system to yield high signal-to-noise observations of these phenomena with high spatial and temporal resolution to study their propagation and evolution through the inner heliosphere. Progress, especially on developing new effective baffling systems, has been very encouraging and has led to feasibility studies of building and flying such an instrument on various spacecraft.

Observations of interplanetary disturbances have also been attempted from the ground in the radio and radar regime. They cannot be observed from the ground in any other regime due to interference by the atmosphere. Observations of Interplanetary Scintillation (IPS) of signals from extra-galactic radio sources show that a dense, turbulent region in the interplanetary medium produced by the passage of a high-speed cloud of plasma can be detected on the ground (e.g., Watanabe & Kakinuma 1984). However, efforts have failed to produce reliable detection of most disturbances that strike the Earth, and the ability of this technique to distinguish between recurrent, corotating high speed streams and transient CMEs is very much in question. Also, the IPS method has relatively poor spatial and temporal (normally once per day) resolution for sensing disturbances. Such marginal detection and analytical capabilities are not adequate for monitoring, analyzing and forecasting geoeffective disturbances (e.g., Leinback et al. 1994). Radar has been used to measure flow speeds of CMEs out to about 5 solar radii (Rodriguez 1995). Having radar velocity measurements near

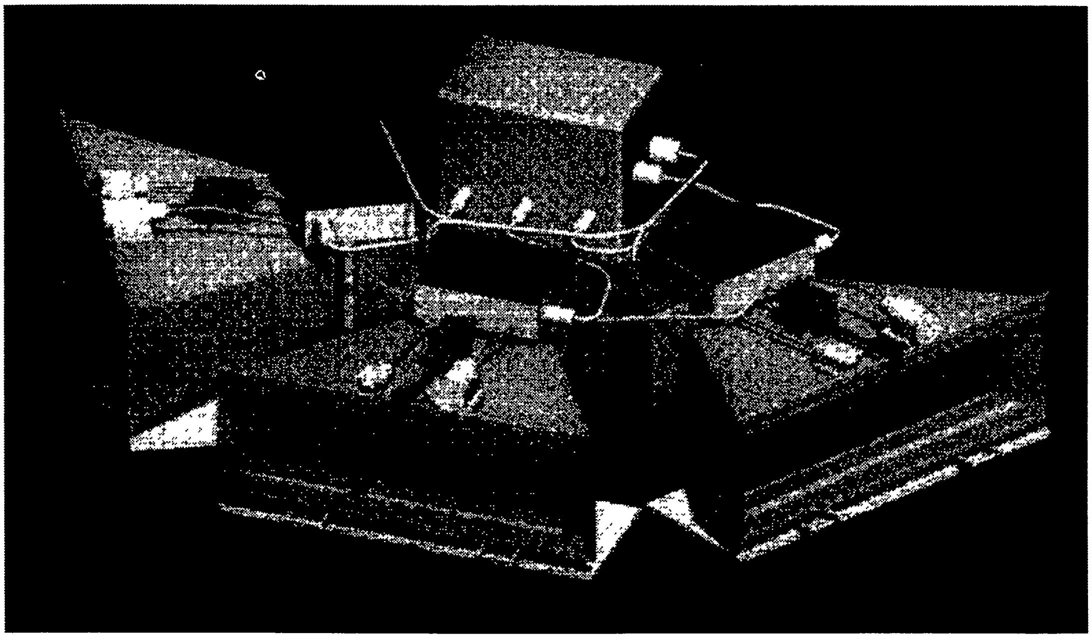

Figure 2. CAD Drawing Showing the Proposed SMEI Instrument

the Sun for a CME along with the continuous imaging of SMEI would permit development of accurate propagation models.

2. Description of Proposed Instrument

SMEI must image faint sources propagating against a bright background. This drives several instrumental requirements, which have been thoroughly documented (cf. Jackson 1988; Jackson et al. 1989; Jackson, Gold & Altrock 1991; Jackson et al. 1994a). Many of the requirements presented in these papers were developed at UCSD and are available from B. V. Jackson and A. Buffington in a series of technical memos. The following specifications were taken from these documents.

A photometric precision of $\sim$ 0.1% is required to separate the relatively faint emissions from CMEs and other propagating disturbances from the greater brightnesses of the zodiacal dust cloud and stars. This zodiacal and stellar background must be subtracted from each sky image, thus requiring precise angular registration of the images (to about 10 millipixels or 0.002°). To reach these limits, and also average out microscopic photometric variation on the CCD, individual star images must span about pixels (Buffington, Hudson, & Booth 1990; Buffington, Booth, & Hudson 1991). Other potential sources of background are scattered sunlight, moonlight and Earth glow. To provide the low stray-light levels needed for these measurements, a combination of aperture baffling of the instrument and optics that produce low-scattered light levels, must reduce stray-light to better than one part in 10^{12}.

The SMEI instrument under development will meet these requirements. The main subsystems of the experiment will consist of three electronic camera/sensor systems and an electronics box with harness (Fig. 2). Each of the three sensor systems will have a wide slit aperture, carefully baffled to minimize stray light, and optics feeding an electronic detector. Baffles that achieve a scattered light reduction of 10^7 to 10^8 have been designed and tested (Jackson et al. 1991). Optical systems reducing stray light by a factor of 10^5 to 10^6 have been designed at UCSD (Abraham et al. 1988; Jackson 1988). The baffle/optical systems will be rigidly mounted to a nadir-pointing spacecraft, whose orbital rotation permits a nearly complete survey of the sky once every 90 min. Each of the three sensors covers a different $3^\circ \times 60^\circ$ field of view (FOV) such that together they view a thin 180°-wide slice of the zenith-facing hemisphere of the sky. The plane of the detector slits will be oriented perpendicular to the spacecraft velocity vector. Thus, during every complete orbit each detector sweeps out a complete circular swath in the sky and, together, the three detectors will cover 180° and will sweep over the entire sky. Each baffle system will have a "Sun sensor" which activates a shutter mechanism to block the detector and prevent its saturation while sunlight or other bright objects are in the FOV. At a minimum, the sensor/shutter system is needed to prevent the detectors from viewing within about 20° of the Sun.

The detector system is perhaps the most critical component of SMEI, and requires a CCD with an extremely uniform response. Several CCD systems are being analyzed to determine their suitability for SMEI. Final choice of the CCD will be based on whether it has sufficient photon-counting capability, sufficiently low readout noise, thermal constraints that can be satisfied and has small inter-pixel and intra-pixel variations. The latter requirement is driven both by the photometric specification and by the need to precisely locate background sources, especially stars.

3. SMEI Science and Forecasting Objectives

SMEI is a prototype for a monitoring system which will improve geomagnetic-disturbance forecasting by identifying solar-generated disturbances and predicting their arrival time at Earth. As demonstrated with HELIOS photometer data, SMEI will be able to track CMEs, shock waves, and structures corotating with the Sun, such as streamers. Because of its high sensitivity and good spatial and temporal resolution on heliospheric scales, SMEI will measure characteristic parameters of CMEs and shocks in the IPM. These characteristics are of fundamental interest because of the role they play in transferring mass and energy from the Sun through the IPM to the Earth where they drive geomagnetic storms. Important parameters of CMEs that SMEI will be able to determine include the mass, pressure, energy, momentum flux, speed, pressure, size scale and shape, and frequency of occurrence.

SMEI will provide measurements vital for understanding the coupling and energy transfer from disturbances in the solar wind to the magnetosphere. Thus, it will provide insight into the causes and development of geomagnetic storms and other transient phenomena which can affect both civilian and military spacecraft and ground systems. When combined with in situ solar wind measurements from an upstream monitor such as WIND, these data will permit measurements of the components of CMEs likely to be most important for magnetospheric coupling. These components include the momentum flux, total pressure (gas plus magnetic), interplanetary magnetic field strength and level of turbulence, and the temporal characteristics of these flows. SMEI alone will provide up to 3 days warning of the arrival of a CME aimed toward the Earth. A combined system consisting of an Earth-orbiting SMEI and an upstream solar wind monitor can provide unprecedented detailed measurements and prediction of an impending storm at the Earth.

SMEI can detect all major mass ejections propagating through near-Earth space. There are more small mass ejections than large ones down to some limit and SMEI can detect them to a threshold similar to the smallest masses observed by the SOLWIND coronagraph, or about $3 \times 10^{14} gm$ (Jackson & Howard 1993). Earth-orbiting coronagraphs such as SOLWIND best observe CMEs over the limb of the Sun and miss or only partially detect those events originating from further onto the solar disk. Although SMEI also must avoid viewing close to the solar disk, it will be able to more-easily detect an Earth-directed mass ejection as it gets closer to the Earth. Unlike a coronagraph, SMEI is designed to work best at large elongation angles from the Sun, and views areas of the sky that have a much smaller range of intensities. Therefore, as mass ejections move out from the Sun, they can be more easily distinguished relative to the background.

There are other heliospheric features that SMEI will measure. It can separate those events which corotate with the Sun from those, like CMEs and shocks, that move nearly radially outward. Corotating structures include sector boundaries and streamers which extend from the Sun, where they form the locus of the source region of the heliospheric current sheet. We can determine the mass-flow and speed within these structures. With appropriate modeling of these interaction regions viewed to the east of the Sun-Earth line by SMEI, we can forecast the arrival at Earth of these denser features of the current sheet, which also can drive geomagnetic disturbances. How mass ejections interact with and or are part of these corotating regions should also be apparent in SMEI data.

Finally, SMEI will detect other features of interest to researchers in space physics and astronomy. The interplanetary sky background is composed primarily of three components: the zodiacal light (the dust component), Thomson-scattered coronal light, and starlight. In terms of its primary mission, these are noise sources to SMEI which can swamp the faint transient plasma features it is trying to detect. However, the data gathered by SMEI on these sources are of fundamental interest in their own right. As with HELIOS, SMEI will make accurate measurements of the zodiacal dust cloud, and possibly the Gegenschein, or counter glow. If we assume SMEI sky bins of 1 sq. deg., fluxes of individual stars will dominate the brightness of many such bins. To remove this stellar contribution, the orientation of each SMEI CCD frame upon the sky must be determined to an accuracy of 0.1°. Individual stars whose brightness has varied will be recognizable through their residue once the background is subtracted. Thus, SMEI will provide a unique long-term data base of discrete variable astronomical phenomena, including variable stars and galaxies, novae and supernovae. Such data are of great interest to astronomers. Comets and their bow shocks can also be detected by SMEI and their plasma and dust components studied. SMEI will also be able to detect near-Earth asteroids (Jackson et al. 1994a).

4. Data Reduction, Analysis and Distribution

The present operational concept is to digitize data continuously from the three detectors, then downlink the data for reduction and all-sky map production on the ground. The initial data set from SMEI will consist of apparent brightness measurements from the cameras, over a 3 by 180° section of sky. These data are then mapped to a position in the sky to an accuracy of 0.1°. The brightness in each sky bin is corrected through a calibration procedure involving the stars present in the FOV.

Initially, data reduction from SMEI will consist of obtaining a sky map of brightnesses at approximately 1° resolution. This sky map will have the stars and long-term background brightness variations removed from the record. The residual brightness, when differenced over time, gives a record of the interplanetary Thomson-scattered flux present with variations longer than one spacecraft orbital period, or about 90 minutes. In calibrated form these maps will be made available on a regular basis to those wishing to use them. The original, uncalibrated sky-bin to sky-bin brightnesses, suitably tagged by time and position, will also be made available on data tapes. These pixel brightness data will be useful for other forms of analyses involving the sky maps, such as for determining the brightnesses and their variations of stellar or galactic sources.

For forecast operations, we need to reduce and analyze the data in as near real time as possible. This will involve mapping brightnesses to a given sky position, removal of stars, differencing from previous images or longer term average map, and presentation of the image in convenient formats, for example, as a contoured printout map or on a monitor screen once per orbit.

We encourage wide dissemination of the appropriately reduced data from the instrument through normal channels. We are prepared to participate with other researchers in the distribution, analysis, and publication of the results using these data. Toward this end, at the appropriate time we will make the data available to the community through the NSSDC in compatible formats.

5. Summary

SMEI represents a unique opportunity to causally link events on the Sun with terrestrial disturbances. Using SMEI in conjunction with other space-based and ground-based instruments, it will be possible to develop a three dimensional view of the portion of the heliosphere traversed by the Earth. SMEI provides a critical, missing element needed for accurate space weather predictions.

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Group Discussion

Fry: Have you considered flying SMEI on a planetary mission? NASA plans 2 launches to Mars every 2 years, for the next 10 years. The viewing geometry would provide better indication of Earth-directed CMEs and their speed. With no moonshine, Mars' albedo is much less than Earth's so light scatter will be diminished. Possible benefits to NASA: Mars–solar wind interaction studies, NASA space science program, and Future astronaut warnings.

Keil: We would be interested in such opportunities. One difficulty might be data transmission rates.

Bornmann: (1). You still need Bz (southward magnetic field) to predict geomagnetic storms – hence the less than optimal success with forecasts.
(2). Are the sizes and intensities of CMEs sufficient with SMEI's 18 degree cone of avoidance to provide confidence that a CME will hit the Earth?

Keil: (1). Bz is still a major problem. We hope to combine SMEI data with models of the solar wind, such as that presented at this workshop by Linker, to give accurate arrival times along with predictions of Bz directions.
(2). Most CMEs observed with HELIOS photometers occupied sufficient angular dimensions that this was not a problem.

Bromage: Will you be augmenting the information obtained from SMEI with results from Interplanetary Simulation observations made from the ground?

Keil: Yes. We would like to build as complete a picture of CMEs as possible.

Dryer: Follow-up on Dr. Bromage's question about IPS: the next few years will bring Mexico, Brazil on-line as part of a world-wide dedicated solar wind monitoring effort. These new observatories will – hopefully! – have their data combined with the existing ones at Ooty, Thalthej, Tokyokawa – and, we hope, Beijing and Puschino. Thus, the original problem with the Cambridge IPS study, namely its poor, single-station, temporal resolution, will be eliminated. I hope that SMEI data can be coordinated with these other observatories' IPS data. The latter will be able to measure (from spectral data) the solar wind velocities and could provide an independent estimate of that parameter as well as that of density.

Keil: An independent source of velocity data will greatly enhance the usefulness of SMEI. It will permit models that distinguish between expansion rate of the cloud and progress towards the Earth, to be developed and applied for more accurate arrival time prediction.

Sagalyn: Steve's paper discussed the purpose and development of the Solar Mass Ejection Instrument (SMEI). While there is a great amount of data that may be obtained from this instrument, its main function is to obtain information on spatial and other physical characteristics of mass ejections from the Sun which may hit the Earth. This data will provide inputs to the forcaster for use in global models 1hr to 72hrs in advance of the CME arrival. The IMF is a very useful adjunct to this data and may be obtained from SWIM/WIND or later ACE.